AD-A152 144 AN OVERVIEW OF STOCHASTIC SIGNAL MODELING(U) NAVAL UNDERWATER SYSTEMS CENTER NEW LONDON CT NEW LONDON LAB D H WOOD ET AL. 20 FEB 85 NUSC/TR-7267 1/1

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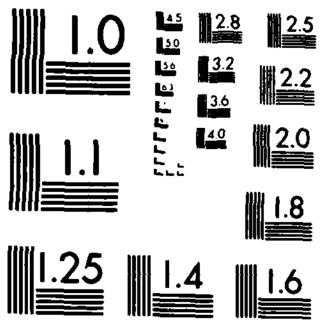

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NUSC Technical Report 7267
20 February 1985

An Overview of Stochastic Signal Modeling

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Preface (U)

(U) This report was prepared under Project No. A65000, EVA Support for Shipboard Sonar (U), Principal Investigator, B. F. Cole (Code 3341). The sponsoring activity is the Naval Sea Systems Command, C. D. Smith (NAVSEA 63R), Director. Funding is provided under Program Element No. 62759N, F. R. Romano (NAVSEA 63R3), Manager. This effort was performed under Subproject SF 59-552A and coordinated with other Navy subprojects through R. W. Farwell (NAVSEA 63R3).

(U) The Technical Reviewer for this report was R. Deavenport (Code 3332).

(U) The authors are indebted to B. F. Cole for his advice and suggestions during the course of this study.

Reviewed and Approved: 20 February 1985

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TR 7267	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN OVERVIEW OF STOCHASTIC SIGNAL MODELING		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David H. Wood J. S. Papadakis		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Underwater Systems Center New London Laboratory New London, CT 06320		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A65000
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Washington, DC 20362		12. REPORT DATE 20 February 1985 13. NUMBER OF PAGES 12
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustics	EVA	Phenomenological
Design Criteria	Fluctuation	Sonar
Deterministic	Modeling	Stochastic
Environmental	Monte Carlo	Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Knowing the average value of a fluctuating acoustics field is not enough to provide criteria for the design of sonar systems. More important are the statistics that measure the decorrelations of the field and its intensity. After discussing the variabilities of the environment that affect the field, this report summarizes the four major approaches to these problems: deterministic, phenomenological, Monte Carlo, and stochastic modeling. Two different courses of action are recommended for computing the desired statistics. In

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the first course, existing models, each dealing with some effects and ignoring others, can be linked to handle the simplest problems. In the second course, a Monte Carlo approach is recommended for more difficult problems, although its generality is gained at the expense of intensive computer usage.

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INTRODUCTION

Throughout this report, we will say that the sound field fluctuates and that each element of the environment varies. We will ask what the statistics of fluctuations of the sound field are. We will want to know the variance of the field and the variance of the intensity and not just their averages. More important for developing systems-design criteria, and much more difficult to compute, are the statistics that measure the decorrelations of the sound field and of its intensity in space, time, and frequency.

In this report, we will discuss the variability of elements in the environment that affect the sound field. Environmental elements in three areas are considered: ocean surface, ocean volume, and ocean bottom. We will discuss the four major approaches to calculating the desired statistics. Two different and parallel courses are recommended to compute the desired statistics.

For the simpler statistics, we recommend linking existing computer models, each dealing with one (or more) of the variations in elements of the environment. We would have to provide an overall structure for these submodels and fill a few gaps for which there is no presently existing model. We will have to accept the fact that this procedure neglects some of the coupling of the effects of variations of different elements. However, a parallel course of action will help to determine when the resulting errors will be small.

For the more difficult statistics, there are too many profound gaps to permit the above approach. A Monte Carlo approach is recommended to produce the desired statistics readily within an existing deterministic broadband model.[1] This simplicity is gained at a high cost in computer time and storage.

THE DESIRED STATISTICS

In a deterministic model of the sound field, one uses a fixed environment without variability to compute[1] the value of the field, which is a complex number at each point in space and time. We shall refer to the square of the absolute value of this complex number as intensity. In a stochastic model, randomly variable elements of the environment are assumed and this means that the field at every point in space and time is a distribution of possible values.[2-6] We are interested in the statistics[7] that summarize the information about the distribution of values of the field at a point. For example, such statistics as the average value at a particular point or at a particular time or at both a particular point and time. Average value of the intensity of the field is another important statistic. (To get this average, we cannot simply take the intensity of an average because, in computing an average, there are generally some cancellations but, in averaging intensity, the values are positive and there are no cancellations). Another very important statistic is the correlation of the field between one point in space and another point in space,

or correlation between the fields at two different times. All of the above low-order statistics are relatively simple to compute with existing computer models.

Even more important,[8] but also much more difficult, are higher-order statistics, such as the correlation of intensity at different points in space and time or in both space and time. The average fluctuations of intensity are another statistic of great interest. Other possibilities include such things as the variance or skewness of the distribution of the fluctuations of intensity. All of these higher-order statistics generally are very difficult to compute efficiently and few computer models are available.

VARIABILITY OF ELEMENTS OF THE ENVIRONMENT

The surface of the ocean has a constantly changing shape, which causes fluctuations in the sound field. The nature of these fluctuations depends on the wavelengths that are present in the acoustic field. There are existing models[9-11] for short wavelengths and long wavelengths but, unfortunately, there is a gap exactly in an area that is of great interest in naval problems. Roughness of the surface also causes backscattering of sound.[12-18] It is difficult to model the manner in which the surface effects interact with refraction[19,20] through the medium, as in multiple-reflection situations. The environmental information about the surface that is needed[20,21] includes at least the distributions of rms wave height and rms roughness of the surface. There are theoretical and empirical results predicting these distributions.[22] Sometimes, for computing high-order statistics, one also needs higher-order correlation functions of the surface as well.

Within the volume of the ocean itself, there is a variability giving rise to fluctuations in the field.[23-32] Some of this variability is thought to be caused by internal waves[33-35] and a great deal of work has been done in modeling[36-40] the effects of these, generally neglecting surface and bottom interactions. Refraction is generally included in the treatment but effects near caustics are seldom included. Another cause of variability is the presence of scatterers distributed through the volume. The information on the variability within the volume of the ocean that is generally required for computer models includes the spectrum of the internal waves. There are models for this spectrum.[33,34] The distributions of scatterers within the ocean must be known in order to use some volume-scattering models. There are some experimental data on these distributions.

The effect of bottom conditions is both the most complicated and the least known of the effects of environmental variability. The surface of the bottom has roughness, of course, which can be treated by models similar to those used for the surface of the ocean.[41,42] However, the effect of roughness is often neglected because of much stronger effects due to the structure of the bottom.[43,44] The sound field generally will penetrate the bottom and interact with the structure in a very complicated way giving rise to effects that are difficult to understand and to model.[44-51] Only now are there emerging models that treat an average profile within the bottom with stochastic variations about that average profile. These models generally neglect the effects of refraction in the water. The information that is desired for modeling the

effect of bottom conditions includes the distribution of variability around the average profile as a function of depth. This distribution is, at this time, generally not known from measurements.[52]

METHODS FOR COMPUTING STATISTICS

There are four principal methods for computing the desired statistics. They are deterministic modeling, phenomenological modeling, Monte Carlo modeling, and stochastic modeling. Some form of each of these four is commonplace in present-day modeling of sound fields in the ocean. For example, deterministic modeling can be used to find the decorrelations caused by the interference of multiple paths of propagation.[53] Phenomenological modeling is often used in computing surface loss in terms of decibels per bounce. Monte Carlo is used in parameter sensitivity studies. Finally, stochastic modeling is used in studies of surface scattering.

In deterministic modeling, one uses an average, or near average, set of environmental information to calculate the field, a complex number, at a particular point and time or frequency.

In the phenomenological approach, the desired fluctuating field is approximated by using the solution of the deterministic problem and adding to it some random variable heuristically derived from the probability distribution of environmental variations.

In the Monte Carlo approach, a sequence of deterministic problems are solved using variations selected at random from the appropriate probability distribution of environmental variations. The desired statistics of the fluctuating field are approximated from the sequence of samples of the field that has been generated.

In the stochastic approach, the random variation of conditions in the ocean are initially incorporated into the mathematical model representing the environment. Even if it is too difficult to solve such a problem, it may be possible to derive a deterministic equation that governs a particular statistic of interest. This equation is solved numerically to get the desired statistic. Each different statistic requires a different equation and solution.

A METHOD FOR COMPUTING FIRST- AND SECOND-ORDER STATISTICS

The simpler statistics are those of first and second order, such as the average value of the field, correlation of the field, and average intensity of the field. For these statistics, there exist computer models that treat variations in environmental elements in at least one of the three areas, surface, volume, or bottom. We recommend that a selection of these could be used as submodels of a stochastic signal model, as outlined in the Spofford report.[54] In this stochastic signal model, the results of the variation of elements of the surface, volume, and bottom are phenomenologically combined, mostly disregarding interactions of these variations. The cited report specifically observes (reference 54, pp. 1-2) that "while higher-order moments are desirable,

the general treatment is beyond the scope of the present effort." In the next section, a parallel Morte Carlo modeling effort is recommended. This modeling would provide a comparison benchmark for the above stochastic signal model and would be extendable to higher-order moments.

We now turn our attention to the selection of submodels. A stochastic model is available, developed by Tappert and Dosier,[55,56] that has the advantage that it allows variability from surface roughness to interact with variability of the volume. The problem is transformed into one that considers a flat surface with volume variability.

Another immediately available model is the phenomenological composite roughness model of McDaniel.[57,58] Any interaction of the surface with the volume and/or the bottom has been implicitly included. A promising surface variability model is under development[59] at Pennsylvania State University based on an exact solution, due to Holford,[60] to scattering from a sinusoidal surface. Presumably this does not include refraction or bottom interaction.

A model of fluctuations due to variability of the volume caused by internal waves has been highly developed by Flatte and his coworkers.[37,61,62] In the latest versions of this model, a user-provided spectrum of internal waves causes a distribution of variations of the sound speed in the water. The solution of the parabolic wave equation for this case was represented as a Feynman path integral by Dashen,[63] who showed that from this one could extract the desired statistics of the resulting fluctuating sound field. This model carries out the computations in an inhomogeneous medium by a method of perturbed ray path. One disadvantage of this model is that it is not correct in the vicinity of caustics. Another disadvantage is that the theoretical predictions depend sensitively on the mean sound-speed profile.

An emerging model by Thomas Clarke is documented in reference 64. He presents a model similar to that of Flatte. By using a "phase screen" representation at intermediate points, he is able to account for refraction, even in the vicinity of caustics, and to compute second moments.

The model developed by McCoy and Berran,[65,66] in a manner of speaking, propagates a correlation function through the medium using a parabolic equation. This is available in the so-called combined effects model (CEM) from the Naval Research Laboratory.[67] Modeling of strong scattering within the volume could be done using the results of Saenger and Brooks.[68]

Present work at Virginia Polytechnic Institute (VPI)[69-71] investigates scattering of acoustic energy by the sediments that cover the ocean floors using two models for ocean-sediment bottoms, (1) The stochastic transport model (STM) and (2) the Markov chain sediment model (MCM).

The STM models the bottom as a lossy refracting medium in which both density and sound speed undergo random variation. The variations of sediment density and sound speed for the STM are assumed to be Gaussian for the initial tasks. Later, a combination of Gaussian and Poisson-type variations are to be studied. The desired output of the model is statistical information about the complex field. A narrow-bandwidth pulsed plane wave is incident on a random pancake-type model. The two-point and two-time mutual coherence function for the complex field is computed. The STM is presently being evaluated for oblique

incidence and no refraction. The predictions of this model are currently being compared with available data that Freese has assembled.[72,73] One of the present goals is to determine the regimes wherein refraction is important (since the ability to neglect refraction significantly simplifies the computations). A longer-range goal is to incorporate more realistic (finite-extent) sources into the modeling.

In the MCM, instead of considering the sediment as a random pancake, it is modeled as a randomly layered refracting medium (Markov chain). Gilbert, also, has used such a model for his simulations. This model needs no further approximations and higher-order moments can, in principle, be evaluated. It also models a point source and seems capable of modeling elastic-media effects. The VPI group recently has begun numerical evaluation of this model and comparisons with Gilbert's simulation, as well as with the data that Freese has assembled.

There are some drawbacks to the VPI models. The STM is very complicated and, since many approximations have to be made, it becomes difficult to keep track of their cumulative effect. Also, going beyond the second moment (mutual coherence function) seems to be very difficult. Stochastic transport theoretic models for higher moments do not currently exist. For the MCM, pulse propagation, while conceptually straightforward, appears to be prohibitive computationally.

COMPUTING HIGHER-ORDER STATISTICS BY MONTE CARLO METHODS

In principle, higher-order statistics, such as correlation of intensity over space, time, and frequency, could be generated by a method like that discussed in the previous section. However, most of the submodels that would compute higher-order statistics, given the variabilities of the surface, volume, and bottom, simply do not exist at this time. Even the partial differential equations governing the higher-order statistics often are not known. There are a few exceptions,[59,74,75] of course, and they would be very important for validating a general Monte-Carlo type model. We recommend a general Monte Carlo model which would generate higher-order statistics and would also be valuable for investigating the range of validity of the stochastic signal model outlined in the previous section. Monte Carlo modeling has been used before[74,75] to test the exceptional computer models that generate higher-order moments.

The advantage of Monte Carlo modeling is that one obtains samples (at each point in space and time) of the distribution of the complex values of the field in a uniform and routine way. Once this is done, any statistic whatever can be computed in a straightforward manner. Many runs of a deterministic model are required to sample adequately both the variability of the environment and the fluctuations of the field. The disadvantage is that a very great amount of computer time and storage are required. These resources are expensive but, likely, are not as expensive as developing whole new special-purpose models, even if the governing equations and analytic skills were available.

CONCLUSIONS

Given that the desired statistics include measures of the fluctuations of intensity due to the variability of the surface, volume, and bottom, Monte Carlo modeling will have to be used. Models for directly predicting the desired statistics do not exist at this time. However, the state of the art in stochastic modeling is adequate for a spread function model for lower-order statistics.

We recommend that two parallel efforts be made. A general-purpose Monte Carlo model is desirable for its higher-order capabilities, despite its high computing costs. A spread function model would be much more efficient for computing lower-order statistics but it would be of limited capability.

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